

Module #3

DESIGN OF EVAPORATOR: INTRODUCTION, TYPES OF EVAPORATORS, METHODS OF FEEDING OF EVAPORATORS, GENERAL DESIGN CONSIDERATION OF EVAPORATOR

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Lecture 1: Introduction and Evaporator Classifications

1. INTRODUCTION

Evaporation is the removal of solvent as vapor from a solution, slurry or suspension of solid in a liquid. The aim is to concentrate a non-volatile solute, such as organic compounds, inorganic salts, acids or bases from a solvent. Common solutes are caustic soda, caustic potash, sodium sulfate, sodium chloride, phosphoric acid, and urea. The most common solvent in most of the evaporation systems is water.

Evaporation differs from the other mass transfer operations such as distillation and drying. In distillation, the components of a solution are separated depending upon their distribution between vapor and liquid phases based on the difference of relative volatility of the substances. Removal of moisture from a substance in presence of a hot gas stream to carry away the moisture leaving a solid residue as the product is generally called drying. Evaporation is normally stopped before the solute starts to precipitate in the operation of an evaporator.

Invention of evaporators: Norbert Rillieux is famous for his invention of the multiple effect pan evaporator for sugar refining process in 1881. Rillieux was born in New Orleans, Louisiana in 1806. He used the steam generated from one pan to heat the sugar juice in the next pan for energy efficient means of water evaporation.

2. TYPE OF EVAPORATORS

Evaporator consists of a heat exchanger for boiling the solution with special provisions for separation of liquid and vapor phases. Most of the industrial evaporators have tubular heating surfaces. The tubes may be horizontal or vertical, long or short; the liquid may be inside or outside the tubes.

2.1. Short-Tube Vertical Evaporators

Short-tube vertical evaporators are the oldest but still widely used in sugar industry in evaporation of cane-sugar juice. These are also known as *calandria* or *Robert* evaporators. This evaporator was first built by **Robert**. It became so common in process industry that this evaporator is sometimes known as *standard evaporator*. Short-tube vertical evaporators consist of a short tube bundle (about 4 to 10 ft in length) enclosed in a cylindrical shell. This is called calandria. A evaporator of this

type is shown in **Figure 3.1**. The feed is introduced above the upper tube sheet and steam is introduced to the shell or steam chest of the calandria. The solution is heated and partly vaporized in the tubes.

The central tube in a calandria is of longer diameter. Typically its downcomer area is taken as 40 to 70% of the total cross sectional area of tubes. The circulation rate through the downcomer/downtake is many times the feed rate. The flow area of the downtake is normally approximately equal to the total tubular flow area.

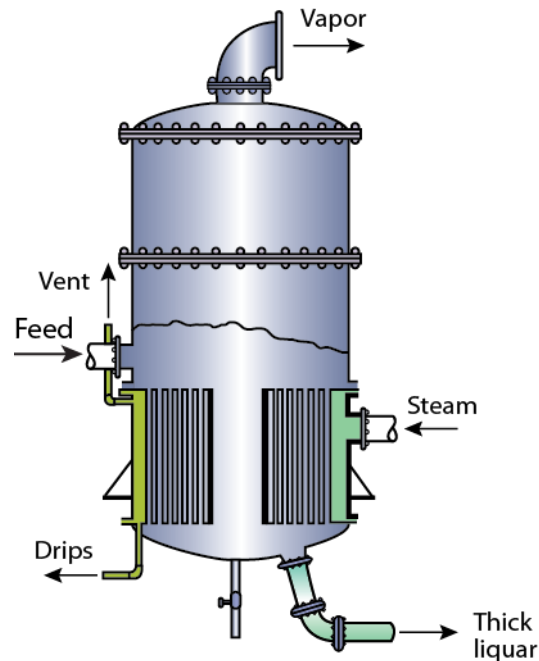


Figure 3.1. Calandria type evaporator.

2.2. Basket-type Vertical Evaporators

The construction and operational features of basket-type evaporators are very similar to those of the standard evaporator except that the downtake is annular. The tube bundle with fixed tube sheets forms a basket hung in the centre of the evaporator from internal brackets. The diameter of the tube bundle is smaller than the diameter of evaporator vessel, thus forming an annular space for circulation of liquid. The tube bundle can be removed for the purpose of cleaning and maintenance and thus basket evaporators are more suitable than standard evaporators for scale forming solutions. The vapor generated strikes a deflector plate fixed close to the steam pipe that reduces entrained liquid droplets from the vapor.

2.3. Long-Tube Vertical Evaporators

This is another most widely employed natural circulation evaporator because it is often the cheapest per unit of capacity. The long vertical tube bundle is fixed with a shell that extends into a larger diameter vapor chamber at the top (**Figure 3.2**). The long-tube vertical (LTV) evaporator consists of one pass shell and tube heat exchanger. In this type of evaporator, the liquid flows as a thin film on the walls of long (from 12 to 30 feet in length) and vertical heated tube. Both rising film and falling types are used. Tube length usually varies from 20 to 65 ft. The main advantage of this type of evaporators is higher heat transfer rate. The feed enters at the bottom and the liquid starts boiling at lower part of the tube. The LTV evaporators are commonly used in concentrating black liquors in the paper and pulp industries.

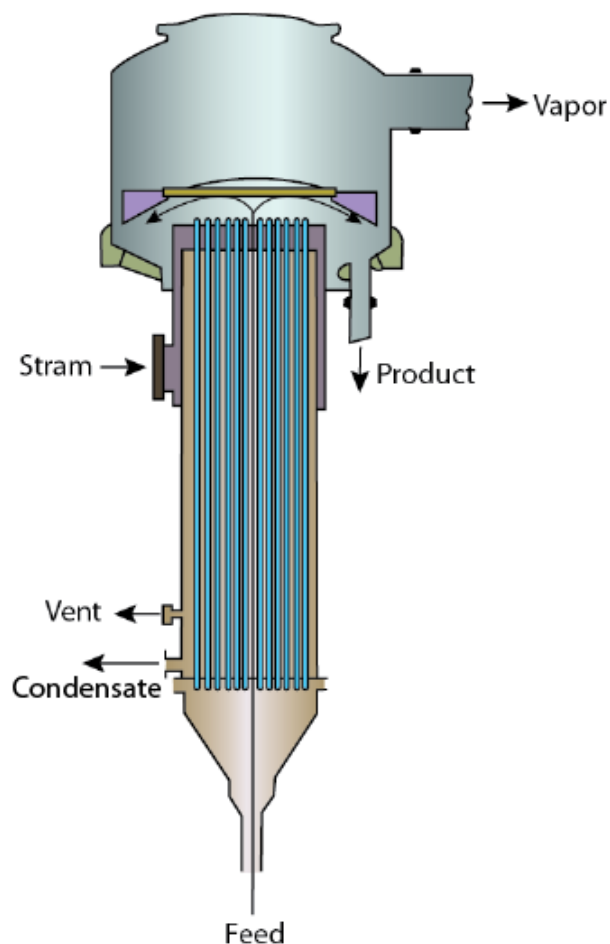


Figure 3.2. Long-Tube Vertical Evaporators.

2.4. *Falling Film Evaporators*

In a falling film evaporator, the liquid is fed at the top of the tubes in a vertical tube bundle. The liquid is allowed to flow down through the inner wall of the tubes as a film. As the liquid travels down the tubes the solvent vaporizes and the concentration gradually increases. Vapor and liquid are usually separated at the bottom of the tubes and the thick liquor is taken out. Evaporator liquid is recirculated through the tubes by a pump below the vapor-liquid separator. This type of evaporator is illustrated in **Figure 3.3**. The distribution of liquid in the inner wall of the tubes greatly affects the performance of this type of evaporator.

The falling film evaporator is largely used for concentration of fruit juices and heat sensitive materials because of the low holdup time. The device is suitable for scale-forming solutions as boiling occurs on the surface of the film.

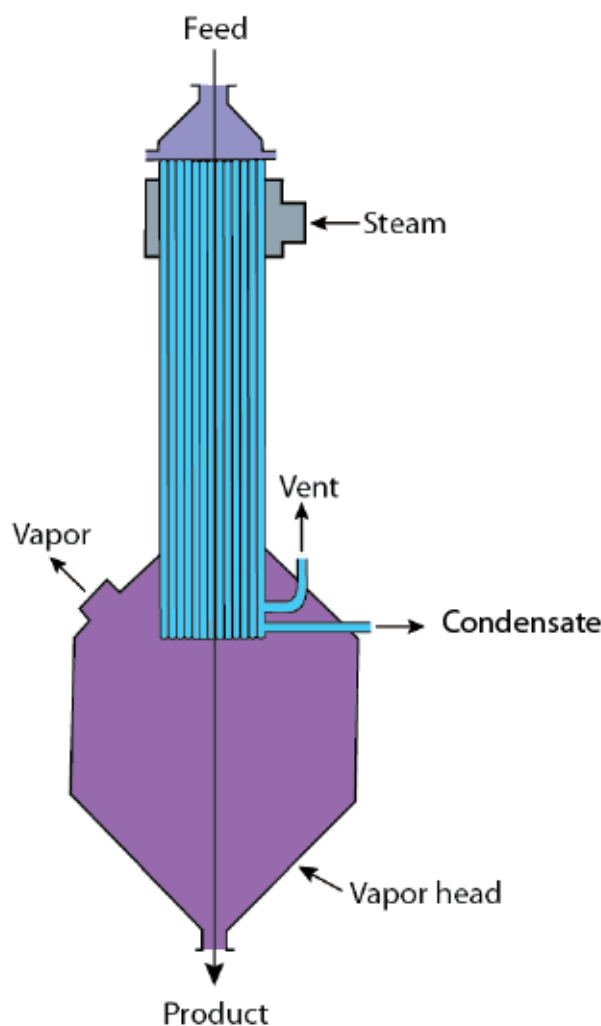


Figure 3.3. Falling-film evaporator.

2.5. Rising or Climbing Film Evaporators

The LTV evaporator is frequently called a rising or climbing film evaporator. The liquid starts boiling at the lower part of the tube and the liquid and vapor flow upward through the tube. If the heat transfer rate is significantly higher, the ascending flows generated due to higher specific volume of the vapor-liquid mixture, causes liquid and vapor to flow upwards in parallel flow. The liquid flows as a thin film along the tube wall. This co-current upward movement against gravity has the advantageous effect of creating a high degree of turbulence in the liquid. This is useful during evaporation of highly viscous and fouling solutions.

2.6. Forced Circulation Evaporators

Forced circulation evaporators are usually more costly than natural circulation evaporators. However the natural circulation evaporators are not suitable under some situations such as:

- highly viscous solutions due to low heat transfer coefficient
- solution containing suspended particles
- for heat sensitive materials

All these problems may be overcome when the liquid is circulated at high velocity through the heat exchanger tubes to enhance the heat transfer rate and inhibit particle deposition. Any evaporator that uses pump to ensure higher circulation velocity is called a forced circulation evaporator. The main components of a forced circulation evaporator are a tubular shell and tube heat exchanger (either horizontal or vertical), a flash chamber (separator) mounted above the heat exchanger and a circulating pump (**Figure 3.4**). The solution is heated in the heat exchanger without boiling and the superheated solution flashes off (partially evaporated) at a lower pressure where reduced in the flash chamber. The pump pumps feed and liquor from the flash chamber and forces it through the heat exchanger tubes back to the flash chamber.

Forced circulation evaporator is commonly used for concentration of caustic and brine solutions and also in evaporation of corrosive solution.

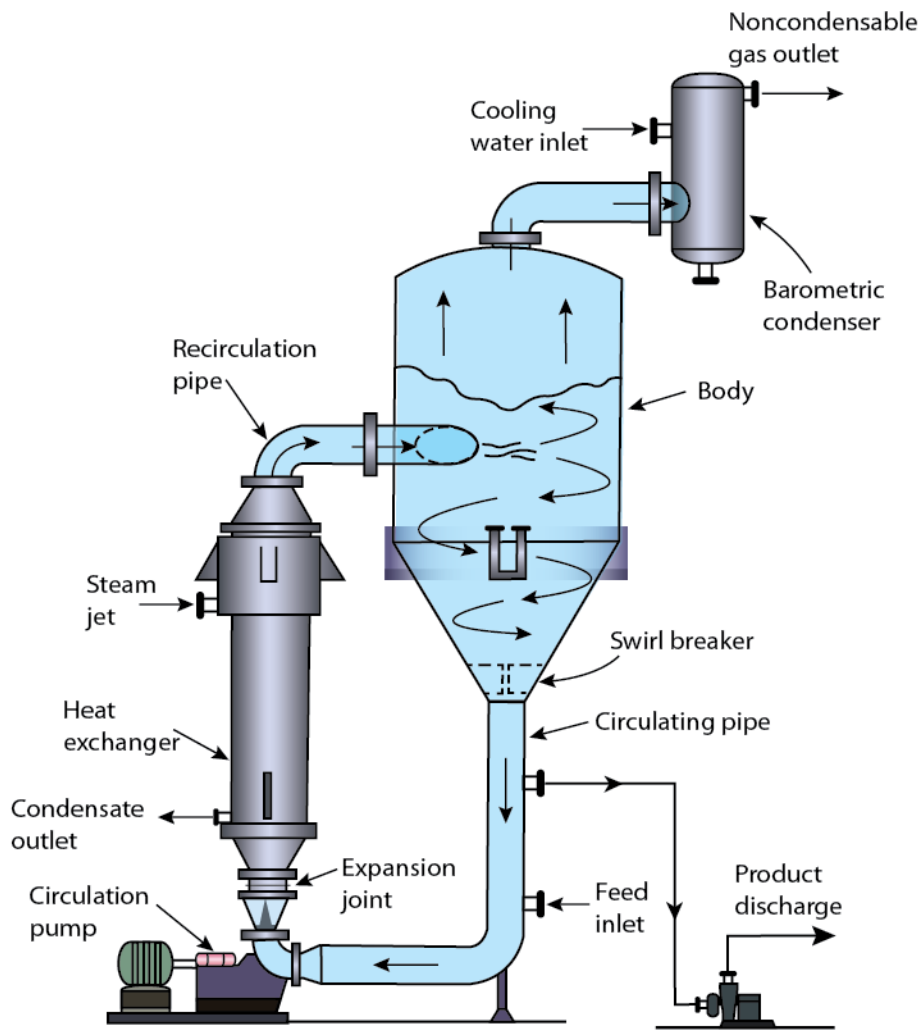


Figure 3.4. Vertical tube forced-circulation evaporator.

2.7 Agitated Thin Film Evaporator

Agitated thin film evaporator consists of a vertical steam-jacketed cylinder and the feed solution flows down as a film along the inner surface of large diameter jacket (**Figure 3.5**). Liquid is distributed on the tube wall by a rotating assembly of blades mounted on shaft placed coaxially with the inner tube. The blades maintain a close clearance of around 1.5 mm or less from the inner tube wall.

The main advantage is that rotating blades permits handling of extremely viscous solutions. The device is suitable to concentrate solutions having viscosity as high as up to 100 P.

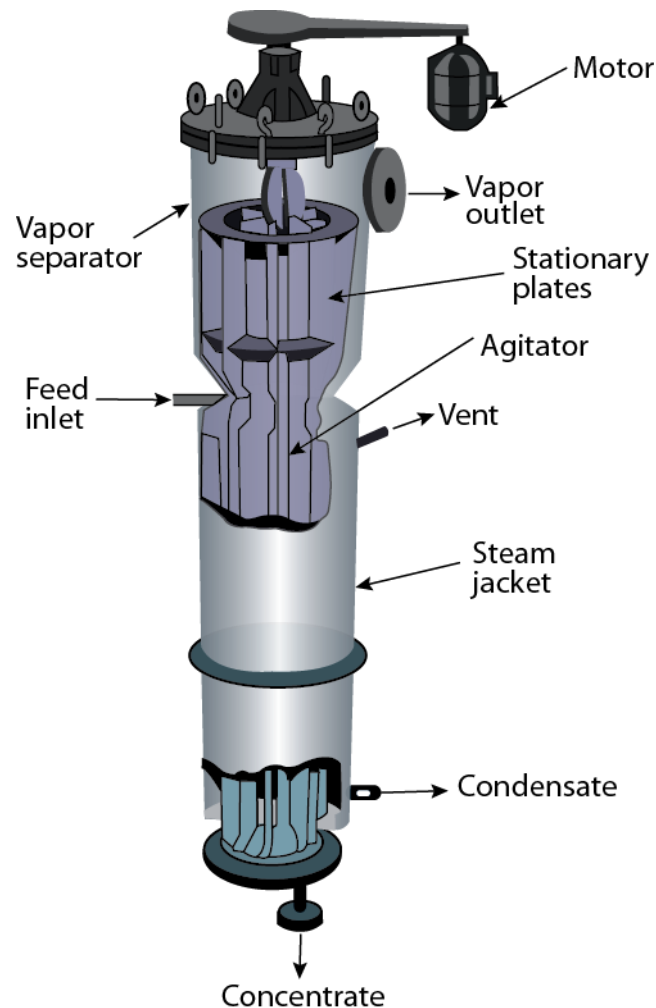


Figure 3.5. Agitated thin-film evaporator.

2.8. Gasketed Plate Evaporator

The gasketed-plate evaporator is also called the plate evaporator because the design is similar to that of a plate heat exchanger. A number of embossed plates with four corner openings are mounted by an upper and a bottom carrying bar. The gasket is placed at the periphery of the plates. The interfering gaskets of two adjacent plates prevent the mixing of the fluids and lead the fluid to the respective flow path through the corner opening (**Figure 3.6**). The fluids may either flow in series or parallel depending on the gasket arrangement.

The heat transfer coefficient is greatly enhanced due to high turbulent flow through narrow passages. This evaporator is suitable for high viscous, fouling, foaming and heat sensitive solutions.

This type of evaporators is mainly used for concentration of food products, pharmaceuticals, emulsions, glue, etc.

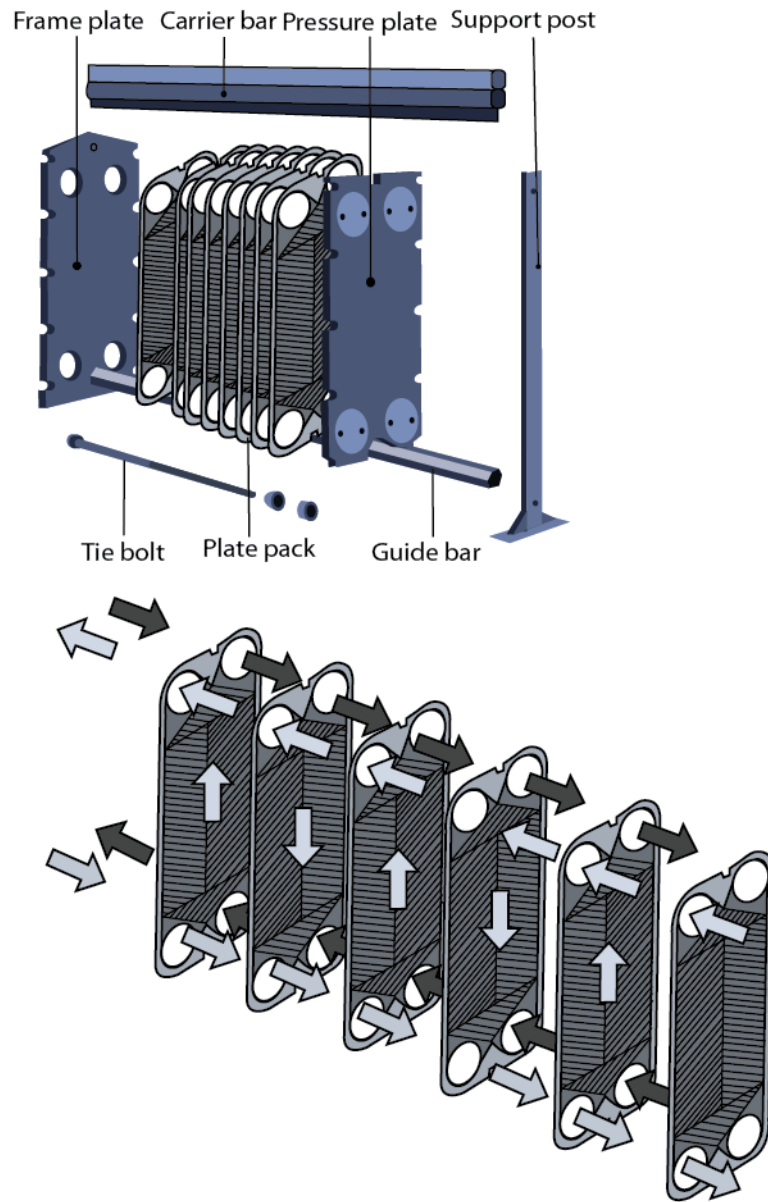


Figure 3.6. Plate-evaporator.

Lecture 2: Methods of Feeding of Evaporators

3. METHODS OF FEEDING OF EVAPORATORS

Evaporators are classified by the number of *effects*. In case of a *single-effect* evaporator, the vapor from the boiling liquor is condensed and the concentrated product is withdrawn from the bottom of the evaporator. Although the operation is simple, the device does not use steam efficiently. Typically 1.1 to 1.3 kg of steam is required to evaporate 1 kg of water.

The steam consumption per unit mass of water evaporated can be increased by putting more than one evaporator in series such that the vapor from one evaporator is used in the second evaporator for heating. The vapor from the second evaporator is condensed and the arrangement is called *double-effect* evaporators. The heat from the vapor generated in the first evaporator is used in the second evaporator. Evaporation of water is nearly doubled in double effect evaporation system compared to single effect per unit mass of steam used. Additional effects can be added in series in the same way to get a *triple-effect* evaporator, *quadruple-effect* evaporator and so on. There are several configurations based on feeding arrangement.

3.1. *Forward feed*

The typical feeding method of multi-effect evaporators is forward. Both feed and steam are introduced in the first effect and the feed passed from effect to effect parallel to the vapor from the earlier effect. Concentration increases from the first effect to the last. Forward feeding operation is helpful when the concentrated product may degenerate if exposed to high temperature. The product is withdrawn from the last effect. It requires a pump for feeding of dilute solution to the first effect. A pump removes thick liquor from the last effect. The liquid from one effect to the next effect also can be transferred without a pump as the flow occurs in the direction of decreasing pressure. The arrangement of forward feeding is shown in **Figure 3.7a**.

3.2. *Backward feed*

In backward feed configuration, the feed enters at the last effect (coldest effect) and is pumped through the successive effects. The product is withdrawn from the first effect (hottest) where the steam is introduced (**Figure 3.7b**). This method of feeding requires a pump between each pair of effects to transfer liquid from lower pressure effects to higher pressure effects. It is advantageous when cold feed entering needs to

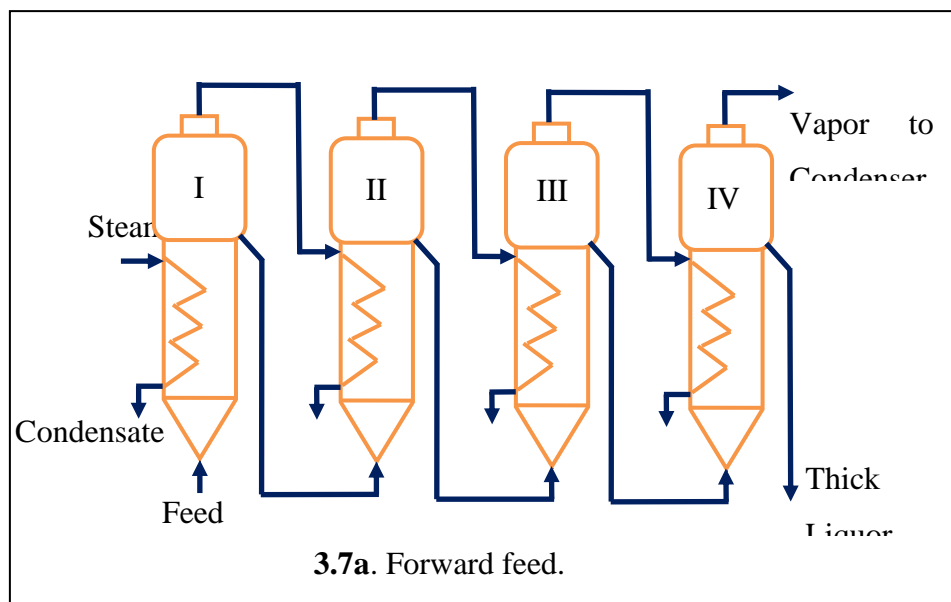
be heated to a lower temperature than in forward feed operation. Backward feed is commonly used when products are viscous and exposure to higher temperature increases the rate of heat transfer due to reduction in viscosity of the liquid.

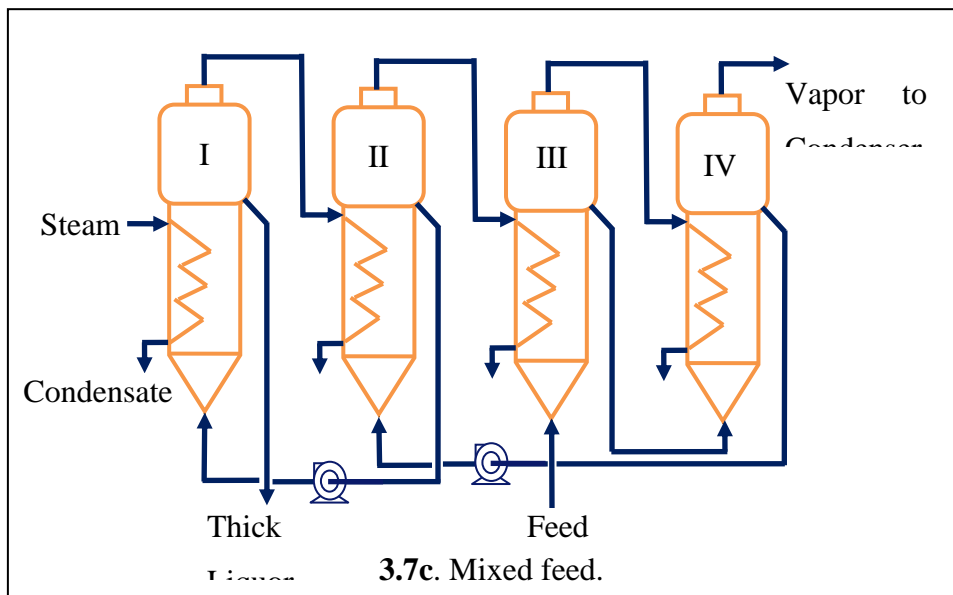
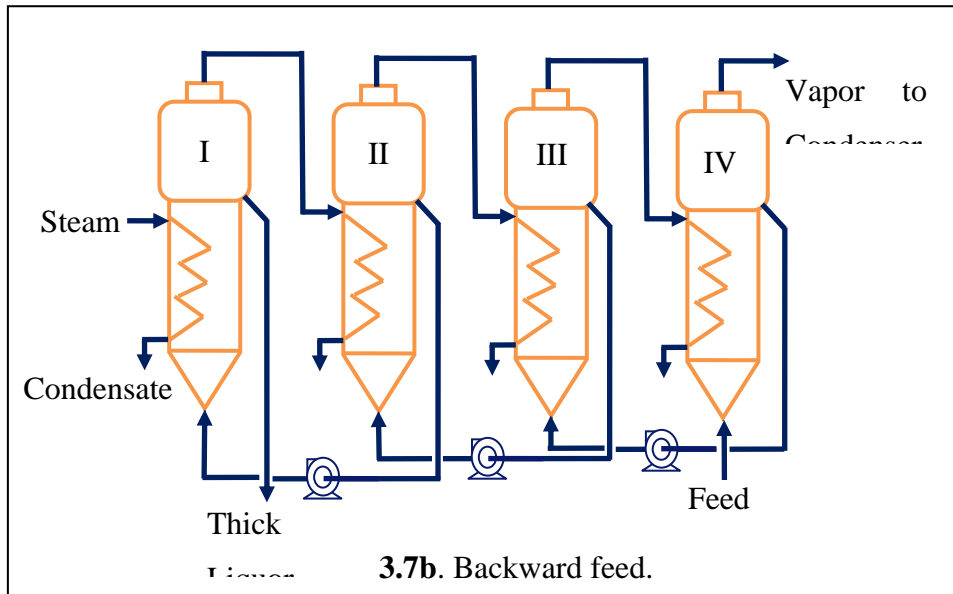
3.3. *Mixed feed*

In the mixed feed operation, the dilute feed liquid enters at an intermediate effect and flows in the next higher effect till it reaches the last effect of the series. In this section, liquid flows in the forward feed mode. Partly concentrated liquor is then pumped back to the effect before the one to which the fresh feed was introduced for further concentration as shown in **Figure 3.7c**. Mixed feed arrangement eliminates some of the pumps needed in backward configuration as flow occurs due to pressure difference whenever applicable.

3.4. *Parallel feed*

The fresh feed is introduced to each effect and in this configuration the product is withdrawn of from the same effect in parallel feed operation (**Figure 3.7d**). In parallel feeding, there is no transfer of liquid from one effect to another effect. It is used primarily when the feed is saturated and the product is solid containing slurry. This is most common in crystallizing evaporators.





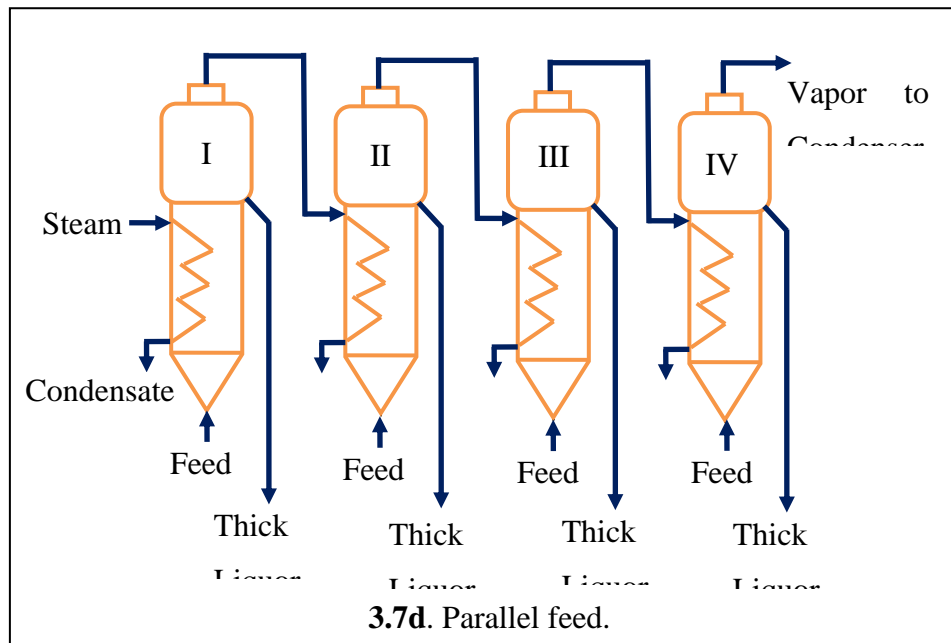


Figure 3.7. Methods of feeding of evaporator: a: forward feed; b: backward feed; c: mixed feed; d: parallel feed.

4. PERFORMANCE OF EVAPORATORS (CAPACITY AND ECONOMY)

The performance of a steam-heated evaporator is measured in terms of its capacity and economy. Capacity is defined as the number of kilogram of water vaporized per hour. Economy (or steam economy) is the number kilogram of water vaporized from all the effects per kilogram of steam used. For single effect evaporator, the steam economy is about 0.8 (<1). The capacity is about n -times that of a single effect evaporator and the economy is about $0.8n$ for a n -effect evaporators. However, pumps, interconnecting pipes and valves are required for transfer of liquid from one effect to another effect that increases both equipment and operating costs.

5. THERMAL/ PROCESS DESIGN CONSIDERATIONS

Many factors must be carefully considered when designing evaporators. The type of evaporator or heat exchangers, forced or natural circulation, feeding arrangement, boiling point elevation, heat transfer coefficient, fouling, tube size and arrangement are all very important.

Types of evaporators have already been discussed and the guidelines for selection of most suitable evaporator are addressed in the next section.

5.1. Tube size, arrangement and materials

The selection of suitable tube diameter, tube length and tube –layout is determined by trial and error calculations. The details are discussed in design of shell and tube heat exchangers (**module #1**). If the pressure drop is more than the allowable pressure drop further adjustments in tube diameter, tube length and tube-layout is required.

A variety of materials including low carbon steel, stainless steel, brass, copper, cupronickel etc. are used. However the selection of tube materials depends on the corrosiveness of the solution and working conditions.

5.2. Heat transfer coefficients

The heat transfer coefficient of condensing steam in shell side is normally very high compared to the liquid side. Therefore tube side (liquid side) heat transfer coefficient practically controls the rate of heat transfer.

The overall heat transfer coefficient should be either known/ calculated from the performance data of an operating evaporator of the same type and processing the same solution. Typical values of overall heat transfer coefficient are given in **Table 3.1**.

Table 3.1. Typical overall heat transfer coefficients in evaporators ([2] page 388).

<i>Type of evaporator</i>	<i>Overall heat transfer coefficient</i>	
	<i>$W.m^{-2} \cdot C^{-1}$</i>	<i>$Btu.ft^{-2}h^{-1} \cdot F^{-1}$</i>
Long-tube vertical evaporator		
Natural circulation	1000-2700	200-550
Forced circulation	2000-7500	400-1500
Short-tube vertical or calandria evaporators	750-2500	150-500
Agitated-film evaporators		
Low to medium viscosity (<1 P)	1800-2700	300-500
High viscosity (> 1P)	1500	300
Falling film evaporators (viscosity <0.1 P)	500-2500	100-500
Rising film evaporators	2000-5000	100-1000

5.3. *Boiling point elevation (BPE)*

Most evaporators produce concentrated liquor having a boiling point considerably higher than that of pure solvent (or water). This phenomenon is called boiling point elevation (BPE). BPE occurs as the vapor pressure of a solution (usually aqueous solution) is less than that of pure solvent at the same temperature. Boiling point of a solution is a colligative property. It depends on the concentration of solute in the solution for a pair of solute and solvent.

BPE of the concentrated liquor reduces the effective temperature driving force compared to the boiling of pure solvent. Equilibrium vapor generated from a solution exhibiting boiling point elevation is superheated with respect to vapor generated during boiling of pure solvent. The vapor is generated at the solution boiling point, which is higher than the pure component boiling point. The vapor, however, is solute free, so it won't condense until the extra heat corresponding to the elevation is removed, thus it is superheated. Therefore the BPE of the concentrated solution must be known for evaporator design.

Determination of BPE: For strong solutions, the BPE data is estimated from an empirical rule known as *Dühring rule*. This states that the boiling point of a given solution is a linear function of the boiling point of pure water at the same pressure. Thus if the boiling point of the solution is plotted against the corresponding boiling point of pure water at the same pressure, a straight line is generated. Different lines are obtained if such plots made for solution of different concentrations. The main advantage is that a Dühring lines can be drawn if boiling points of a solution and water (read from steam table) at two different pressures are known. This line can be used to predict boiling point of a solution at any pressure. A Dühring plot for the NaOH-water system can be found in heat transfer text books ([1] (page 472) and [2] (page 386)).

5.4. Selection of suitable evaporator

The selection of the most suitable evaporator type depends on a number of factors. Mainly these are: (i) throughput, (ii) viscosity of the solution (and its increase during evaporation), (iii) nature of the product and solvent (such as heat sensitivity and corrosiveness), (iv) fouling characteristics and, (v) foaming characteristics. A selection guidelines based on these factors is given in **Figure 3.8**.

Evaporator type	Feed condition							Suitable for heat sensitive material
	Viscosity, cP			Foaming	Scaling or fouling	Crystals producing	Solids in suspension	
	High viscosity >1000	Medium viscosity 100 to 1000	Low viscosity <100					
Calandria (short tube vertical)								No
Forced circulation								yes
Falling film								no
Natural circulation								no
Agitated film (Single pass)								yes
Long tube falling film								yes
Long tube raising film								yes

Figure 3.8. Selection guide of evaporators [3].

6. MECHANICAL DESIGN CONSIDERATIONS

Temperature and pressure are the two important factors that affect the mechanical design of evaporator systems. Many other factors like startup, shutdown, upset, dryout, external loading from supports, pulsating pressure, wind loading, earthquake load etc. also significantly affect the evaporator operation. Various factors are considered that affect the mechanical design of equipment and their affect is detailed in heat exchanger design (**module #1**). Here the temperature and pressure factors are outlined below in brief.

Operating temperature and pressure: The operating temperature is the temperature that is maintained for the specified operation of the metal vessel suitably selected during design. The operating pressure is the pressure at the top of a pressure vessel. However if it's a tall vessel static hydraulic head even during mal-operation needs to be consider.

Design temperature and pressure: It is important to determine both minimum and maximum anticipated operating temperature and pressure in order to obtain the design temperature and pressure. The design pressure is generally is the sum of the maximum allowable pressure and the static head of the fluid in the pressure vessel. The combination of temperature and pressure affect the mechanical design of the equipment. Much of design considerations are also related pressure design too.

Maximum allowable working pressure: The maximum allowable working pressure is the maximum pressure to which the equipment can be safely operated. Generally, it should not be less than the maximum anticipated operating pressure divided by a factor of 0.90 [4].

Thermal expansion: Differential thermal expansion between various parts of equipment has a significant effect on the mechanical design. There may be a significant difference of expansion between the shell and the tube side because of temperature difference of two fluids. Thermal expansion may also determine the way in which tubes are fixed to the tube sheet. Usually a suitable expansion joint is centrally placed between two segments of the shell when the differential expansion may be large.

Lecture 3: Thermal Design Calculation

7. THERMAL DESIGN CALCULATION

7.1. *Single effect calculations*

Single effect evaporator calculations are pretty straight forward. The latent heat of condensation of the steam is transferred through the heating surface to vaporize water from a boiling solution. Therefore two enthalpy balance equations are required in order to calculate the rate of solvent vaporization and the rate of required input heat.

Generally it is possible to solve the energy and the material balance equations analytically by a sequential approach. The following assumptions are made to develop the mass and energy balance equations:-

- there is no leakage or entrainment
- the flow of non-condensable is negligible
- heat loss from the evaporator system is negligible

From the enthalpy data of the solutions, steam and condensate, the rate of heat input or the rate of steam flow can be calculated. The overall heat transfer coefficient U_D (including dirt factor) should be either known from the performance data of an operating evaporator of the same type and processing the same solution or a reasonable value can be selected from the standard text books ([1] **Table 16.1 page 475**; [2] **Table 9.2 page 388**). With this information the required area of heat transfer can be estimated.

Calculate the tube-side and shell-side pressure drop using the method discussed during design of shell & tube exchanger from specified values of the tube length, diameter and the tube layout (refer **module #1** for detail calculations). If the pressure drop value is more than the corresponding allowable pressure drop, further adjustments in the heat exchanger configuration will be required.

7.2. *Multiple effect calculations*

Typically, multiple effect evaporator calculations require a trial-and-error approach as many of the necessary properties depend on unknown intermediate temperatures. Often the heat transfer areas in all effects are considered to be equal. Use of equal size evaporator in all effects, reduces the cost of equipment significantly. In a typical evaporator problem, you are provided with the supply pressure and temperature of

steam, the operating pressure of the final effect, the feed and concentrations. The designer is often required to have trial estimates of overall heat transfer coefficients.

The overall strategy is to estimate intermediate temperatures. The energy and material balance equations are solved sequentially to determine the heat transferred in each effect and the heat transfer area. If the areas are not equal, the calculation is repeated to revise the intermediate temperatures and the procedure is repeated till the heat transfer area in all effects are equal.

The arrangement of a forward feed triple effect evaporator is shown in **Figure 3.9**.

The energy balance equations in all effects are given below:

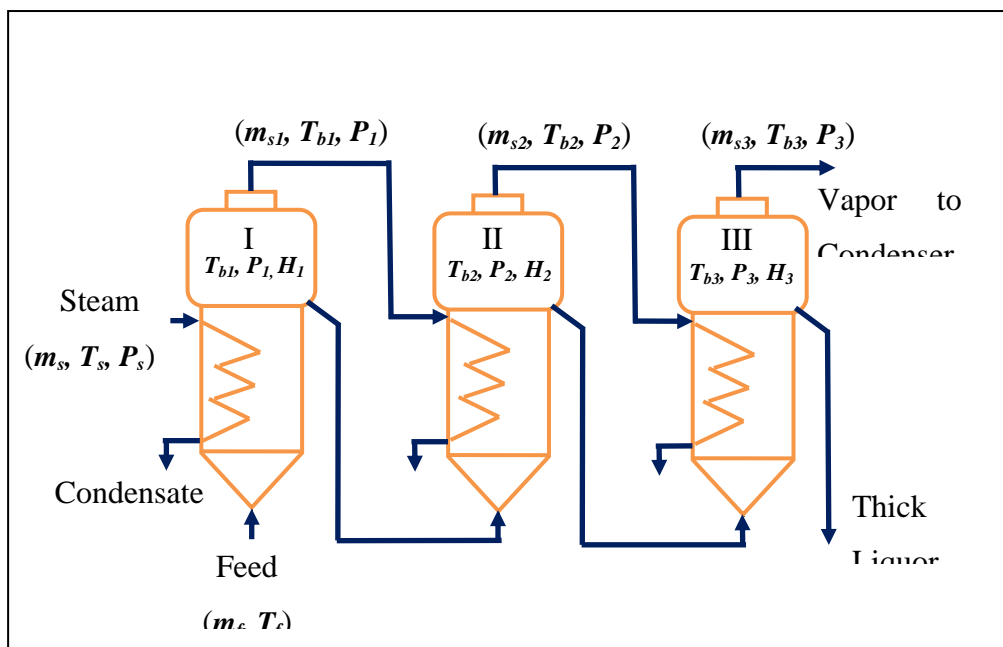


Figure 3.9. Flow rates and pressure in a triple effect evaporator ([2] page 399).

Effect I:

$$m_f H_f + m_s H_s = (m_f - m_{s1}) H_1 + m_{s1} H_{s1} + m_s H_{l1} \quad (3.1)$$

If the sensible heat of the steam is neglected this equation can be rewritten as-

$$m_f H_f + m_s \lambda_s = (m_f - m_{s1}) H_1 + m_{s1} H_{s1} \quad (3.2)$$

Effect II:

$$(m_f - m_{s1}) H_1 + m_{s1} \lambda_{s1} = (m_f - m_{s1} - m_{s2}) H_2 + m_{s2} H_{s2} \quad (3.3)$$

Effect III:

$$(m_f - m_{s1} - m_{s2}) H_2 + m_{s2} \lambda_{s2} = (m_f - m_{s1} - m_{s2} - m_{s3}) H_3 + m_{s3} H_{s3} \quad (3.4)$$

where,

m_{sk} is the rate of vapor generated in the k^{th} effect

m_f and m_s are the feed and steam flow rate

H_k is the enthalpy of the solution leaving the k^{th} effect at T_s and P_s

H_{sk} is the enthalpy of vapor (steam) generated in the k^{th} effect

H_{lk} is the enthalpy of liquid in the k^{th} effect

λ_s is latent heat of steam introduced in the 1st effect at P_s .

λ_{s1} and λ_{s2} are the latent heats of steam condensation at pressure P_1 and P_2 respectively.

If U_{D1} , U_{D2} and U_{D3} are the corresponding overall heat transfer coefficients and A_1 , A_2 and A_3 are the heat transfer area required, then it may be written as -

$$\text{Effect I: } Q_1 = m_s \lambda_s = U_{D1} A_1 (T_s - T_{b1}) = U_{D1} A_1 \Delta T_1 \quad (3.5)$$

$$\text{Effect II: } Q_2 = m_{s1} \lambda_{s1} = U_{D2} A_2 (T_{w1} - T_{b2}) = U_{D2} A_2 \Delta T_2 \quad (3.6)$$

$$\text{Effect III: } Q_3 = m_{s2} \lambda_{s2} = U_{D3} A_3 (T_{w2} - T_{b3}) = U_{D3} A_3 \Delta T_3 \quad (3.7)$$

where,

Q_k is the quantity of heat transferred in k^{th} effect

T_{bk} is the boiling point of the solution in k^{th} effect at the prevailing pressure

T_s is the steam temperature condensing in the 1st effect

$(T_{bk} - T_{wk})$ is the boiling point elevation in the k^{th} effect, where T_{wk} is the boiling point of pure solvent (water) in k^{th} effect at the prevailing pressure

Eqs. 3.2 to 3.7 are solved to calculate the heat transfer area by trial-and-error calculations.

The calculation steps can be summarized as follows

1. Initially temperature in each effect is estimated. To make this estimation, it is assumed that the heat transfer area in all effects is equal. This leads to:

$$U_{D1} A_1 \Delta T_1 = U_{D2} A_2 \Delta T_2 = U_{D3} A_3 \Delta T_3 \quad (3.8)$$

Determine the overall temperature drop between the steam in the 1st effect and the saturation temperature of the last effect (considering the BPE in all effects).

$$\Delta T_{tot} = \Delta T_1 + \Delta T_2 + \Delta T_3 = (T_s - T_{w3}) - \sum BPE \quad (3.9)$$

$$\text{where, } \sum BPE = (T_{b1} - T_{w1}) + (T_{b2} - T_{w2}) + (T_{b3} - T_{w3}) \quad (3.10)$$

- Calculate the total amount of solvent vaporized from the feed and product concentration and feed flow rate. It is assumed that heat transfer rate in each effect is roughly equal. This signifies that the rates of vaporization in each effect are also roughly equal. Calculate the approximate vaporization rate in each effect (it is one-third of total amount of solvent vaporized in one effect in case triple effect system). Calculate the concentration in each effect and find out the *BPE* in each effect. Then calculate the overall temperature drop (ΔT_{tot}).
- Redistribute the overall temperature drop (ΔT_{tot}) among all the effects. Since the areas are the same ($A_1 = A_2 = A_3$), the temperature difference in each effect is roughly proportional to the overall heat transfer coefficients.

$$\begin{aligned}
 U_{D1}\Delta T_1 &= U_{D2}\Delta T_2 = U_{D3}\Delta T_3 \\
 \Delta T_2 &= \Delta T_1 \left(\frac{U_{D1}}{U_{D2}} \right), \quad \Delta T_3 = \Delta T_1 \left(\frac{U_{D1}}{U_{D3}} \right) \\
 \Delta T_{tot} &= \Delta T_1 + \Delta T_2 + \Delta T_3 = \Delta T_1 \left(1 + \frac{U_{D1}}{U_{D2}} + \frac{U_{D1}}{U_{D3}} \right)
 \end{aligned} \tag{3.11}$$

Thus, calculate ΔT_1 , ΔT_2 and ΔT_3 .

- Use the calculated value of ΔT_1 , ΔT_2 and ΔT_3 ; and the composition estimated to calculate the enthalpy values. The same reference temperatures for enthalpy must be used for all streams, including those taken from steam tables, etc. Solve the enthalpy balance equation sequentially to find out m_s , m_{s1} and m_{s2} .
- Use heat transfer equations to calculate the heat transfer area for each effect.

$$A_1 = \frac{m_s \lambda_s}{U_{D1} \Delta T_1}, \quad A_2 = \frac{m_{s1} \lambda_{s1}}{U_{D2} \Delta T_2}, \quad A_3 = \frac{m_{s2} \lambda_{s2}}{U_{D3} \Delta T_3} \tag{3.12}$$

- Compare the areas calculated. If they are not equal, repeat the calculation. Using the areas obtained to revise the temperature estimates. The recommended approach is to use the ratio of the calculated heat transfer area for an effect to the arithmetic mean of the calculated areas as shown:

$$\Delta T_{1,new} = \Delta T_1 \left(\frac{A_1}{A_{mean}} \right) \tag{3.13}$$

Repeat the calculations until the area of each effect is equal.

The procedure above discussed is applicable for forward feed evaporators. The energy balance equation can developed accordingly for backward feed system. Here also the area for each effect is considered to be equal.

The heat transfer area required to obtain the product purity from a specified feed is illustrated in the next example for forward feed evaporator system.

Lecture 4: Solved Example

Design problem

A 5% aqueous solution of a high molecular weight solute has to be concentrated to 40% in a forward-feed double effect evaporator at the rate of 8000 kg.h^{-1} . The feed temperature is 40°C . Saturated steam at 3.5 kg.cm^{-2} is available for heating. A vacuum of 600 mm Hg is maintained in the second effect. Calculate the area requirements, if calandria of equal area are used. The overall heat transfer coefficients are 550 and $370 \text{ kcal.h}^{-1}\text{m}^{-2} \text{ }^\circ\text{C}^{-1}$ in the first and the last effect respectively. The specific heat of the concentrated liquor is $0.87 \text{ kcal.kg}^{-1}\text{ }^\circ\text{C}^{-1}$.

SOLUTION

Part 1. Thermal design

Pressure in effect I to be decided.

Pressure in effect II = $760 - 600 = 160 \text{ mm Hg}$

Boiling point at this pressure = 60°C (from steam table)

(high molecular wt. solute, BPE is neglected)

Latent heat vapor generated in effect II at 160 mm Hg (0.2133bar) = 563 kcal.kg^{-1}
(λ_{s_2})

Heating steam is at 3.5 kg.cm^{-2} gauge; temp (T_s) = 148°C ; Latent heat (λ_s) = 506 kcal.kg^{-1}

Feed rate = 8000 kg.h^{-1} , Solute content = 5%

Final concentration = 40%

Solid in = $8000 \times 0.05 = 400 \text{ kg.h}^{-1}$, water in = $8000 - 400 = 7600 \text{ kg.h}^{-1}$

Product out (40% solid) = $400/0.40 \text{ kg.h}^{-1}$
= 1000 kg.h^{-1}

Water out with the product = $1000 (1 - 0.40) \text{ kg.h}^{-1}$
= 600 kg.h^{-1}

Total evaporation rate in two effects ($m_{s_1} + m_{s_2}$) = $7600 - 600 = 7000 \text{ kg.h}^{-1}$
(3.A)

Allow equal areas to two effects, i.e., $U_{D_1}\Delta T_1 = U_{D_2}\Delta T_2$

$\Delta T_{tot} = \Delta T_1 + \Delta T_2 = 148 - 60 = 88^\circ\text{C}$

$$U_{D1} = 550, U_{D2} = 370 \text{ kcal.h}^{-1}\text{m}^{-2} \text{ }^{\circ}\text{C}^{-1} \Rightarrow \Delta T_1 = 35.4 \text{ }^{\circ}\text{C} \ \& \ \Delta T_2 = 52.6 \text{ }^{\circ}\text{C} \quad (3.11)$$

Temperature of the vapor leaving effect I (T_{b1}) = $148 - 35.4 = 112.6 \text{ }^{\circ}\text{C}$

Latent heat vapor generated in effect I at $112.6 \text{ }^{\circ}\text{C} = 531 \text{ kcal.kg}^{-1}$ (λ_{s1})

$$\text{Energy balance for effect I: } m_f H_f + m_s \lambda_s = (m_f - m_{s1}) H_1 + m_{s1} H_{s1}$$

(3.2)

Enthalpy values: reference temperature = $112.6 \text{ }^{\circ}\text{C}$ (temp of solution leaving effect I)

$$H_f = (40 - 112.6)(1 \text{ kcal/ kg } ^{\circ}\text{C}) = -72.6 \text{ kcal/ kg}$$

$$H_1 = 0 \text{ kcal/ kg (w.r.t. the reference temperature of } 112.6 \text{ }^{\circ}\text{C)}$$

$$\lambda_s = 506 \text{ kcal/ kg; } \lambda_{s1} = 531 \text{ kcal/ kg}$$

$$\therefore (8000)(-72.6) + m_s(506) = (8000 - m_{s1})(0) + m_{s1}(531)$$

$$\Rightarrow m_s = 1.05m_{s1} + 1148 \quad (3.B)$$

Energy balance for effect II:

$$(m_f - m_{s1}) H_1 + m_{s1} \lambda_{s1} = (m_f - m_{s1} - m_{s2}) H_2 + m_{s2} H_{s2} \quad (3.$$

3)

Enthalpy values: reference temperature = $60 \text{ }^{\circ}\text{C}$ (temp of solution leaving effect II)

$$H_1 = (112.6 - 60)(0.94 \text{ kcal/ kg } ^{\circ}\text{C}) = 49.4 \text{ kcal/ kg}$$

(Specific heat of the solution leaving the 1st effect is taken as the mean value of the sp.

heat of feed and the concentrated liquor, i.e., $\frac{1+0.87}{2} = 0.94$)

$$H_2 = 0 \text{ kcal/ kg (w.r.t. the reference temperature of } 60 \text{ }^{\circ}\text{C)}$$

$$\lambda_{s1} = 531 \text{ kcal/ kg; } \lambda_{s2} = 563 \text{ kcal/ kg}$$

$$\therefore (8000 - m_{s1})(49.4) + m_{s1}(531) = (8000 - m_{s1} - m_{s2})(0) + m_{s2}(563)$$

$$\Rightarrow m_{s2} = 0.855m_{s1} + 702.6$$

(3.C)

Solving Eqs. 3.A, 3.B and 3.C for m_s , m_{s1} and m_{s2} :

$$m_s = 4713; m_{s1} = 3395 \text{ and } m_{s2} = 3605 \text{ kg/ h}$$

$$\text{Areas: } A_1 = \frac{m_s \lambda_s}{U_{D1} \Delta T_1} = \frac{(4713)(506)}{(550)(35.4)} = 122.5 \text{ m}^2;$$

$$A_2 = \frac{m_{s1} \lambda_{s1}}{U_{D2} \Delta T_2} = \frac{(3395)(531)}{(370)(52.6)} = 92.6 \text{ m}^2$$

The areas in the two effects are not equal. Revised calculation is required.

The revised temperature difference in 1st effect, $\Delta T_1 = 40^\circ\text{C}$ and $\Delta T_2 = 48^\circ\text{C}$ taken for the calculation (you may also continue the calculation with this revised value $\Delta T_{1,new} = 38.84^\circ\text{C}$) (3.13)

Temperature of the saturated vapor from the first effect = $148 - 60 = 108^\circ\text{C}$

Corresponding evaporator drum pressure = 1.2116 bar

Latent heat of the vapor leaving the 1st effect at $108^\circ\text{C} = 530 \text{ kcal/kg}$ (λ_{s1})

Corresponding pressure in the vapor drum = **1.3317 bar**

Revised calculation: Energy balance for effect I (reference temperature 108°C)

$$\therefore (8000)(-72.6) + m_s(506) = (8000 - m_{s1})(0) + m_{s1}(530) \quad (3.2)$$

$$\Rightarrow m_s = 1.047m_{s1} + 1075$$

(3.D)

Revised calculation: Energy balance for effect II (reference temperature 60°C)

$$\therefore (8000 - m_{s1})(0.94)(108 - 60) + m_{s1}(530) = (8000 - m_{s1} - m_{s2})(0) + m_{s2}(563) \quad (3.3)$$

$$\Rightarrow m_{s2} = 0.8612m_{s1} + 641$$

(3.E)

Solving 3.A, 3.D and 3.E, $m_s = 4652$; $m_{s1} = 3417$ and $m_{s2} = 3583 \text{ kg/h}$

$$\text{Areas: } A_1 = \frac{m_s \lambda_s}{U_{D1} \Delta T_1} = \frac{(4652)(506)}{(550)(40)} = 107 \text{ m}^2; \quad A_2 = \frac{m_{s1} \lambda_{s1}}{U_{D2} \Delta T_2} = \frac{(3417)(530)}{(370)(48)} = 102 \text{ m}^2$$

These areas are fairly close, use $A_1 = A_2 = 104 \text{ m}^2$ plus overdesign. About 10% excess area will provide a reasonable overdesign.

Tube details:

Let us select 1¼ inch nominal diameter, 80 schedule, brass tubes of 12 ft in length

Outer tube diameter (d_o) = 42.16 mm

Inner tube diameter (d_i) = 32.46 mm

Tube length (L) = 12 ft = 3.6576 m

Surface area of each tube (a) = $\pi \times d_o \times L = \pi \times 42.164 \times 10^{-3} \times 3.6576 = 0.4845 \text{ m}^2$

Number of tubes required providing 10% overdesign (N_t) = $A/a = (115/0.4845) \approx 238$

Tube pitch (triangular), $P_T = 1.25 \times d_o = 1.25 \times 42.164 = 52.71 \approx 53 \text{ mm}$

$$\begin{aligned} \text{Total area occupied by tubes} &= N_t \times (1/2) \times P_T \times P_T \times \sin\theta \quad (\text{where } \theta = 60^\circ) \\ &= 238 \times 0.5 \times (53 \times 10^{-3})^2 \times 0.866 \end{aligned}$$

$$= 0.2894 \text{ m}^2$$

This area is generally divided by a factor which varies from 0.8 to 1 to find out the actual area. This allows for position adjustment of peripheral tubes as those can't be too close to tube sheet edge.

Actual area required = $0.2894 / 0.9$ (0.9 is selected)

$$= 0.3216 \text{ m}^2$$

The central downcomer area is generally taken as 40 to 70% of the total cross sectional area of tubes. Consider 50% of the total tube cross sectional area.

Therefore, downcomer area = $0.5 \times [N_t \times (\pi/4) \times d_o^2]$

$$= 0.5 \times [238 \times (\pi/4) \times (0.04216)^2]$$

$$= 0.1661 \text{ m}^2$$

Downcomer diameter = $\sqrt{[(4 \times 0.1661) / \pi]}$

$$= \mathbf{0.460 \text{ m}}$$

Total area of tube sheet in evaporator = downcomer area + area occupied by tubes

$$= 0.1661 + 0.3216 \text{ m}^2$$

$$= 0.4877 \text{ m}^2$$

Tube sheet diameter = $\sqrt{[(4 \times 0.4877) / \pi]}$

$$= \mathbf{0.788 \text{ m}}$$

Lecture 5: Mechanical Design

Part 2. Mechanical design

A few basic parts of mechanical design of evaporator are shown below. The systematic approach of mechanical design of shell and tube heat exchanger is discussed in **module #1**.

Process design parameters and materials of construction:

Consider a standard vertical short tube evaporator (calandria type) for this service

Evaporator drum operated at 1.3317 bar pressure

Amount of water to be evaporated = 7000 kg/hr

Heating surface required $A = 115 \text{ m}^2$

Steam is available to first effect at 3.433 bar pressure

Density of 5% feed liquid (ρ_l) = 1050 kg/m³ (assumed)

Density of water vapor (ρ_v) = $\frac{PM}{RT}$ at saturated vapor temperature in the first effect

(108°C).

$$= (1.3317 \times 18) / (8.314 \times 10^{-5} \times 381)$$

$$= 0.757 \text{ kg/m}^3$$

Design pressure (P) = 5% more than the maximum working pressure

$$= 1.05 \times 3.433$$

$$= 3.605 \text{ bar}$$

$$= 3.6749 \text{ kgf/cm}^2$$

Volumetric flow rate of water vapor (V): $7000 / (0.757 \times 3500) = 2.57 \text{ m}^3/\text{s}$

Evaporator shell: low carbon steel (IS-2062)

Tube material: brass

Permissible stress for low carbon steel = 980 kg/cm²

Modulus of elasticity for low carbon steel = $19 \times 10^5 \text{ kg/cm}^2$

Modulus of elasticity for brass = $9.5 \times 10^5 \text{ kg/cm}^2$

Conical head at bottom: cone angle = 120°

Conical head at top: cone angle = 120°

1. Check for tube thickness

The tube thickness is given by $t_t = \frac{Pd_i}{2fJ - P}$

The permissible stress of brass (f) = 538 kg/cm²; Welding or joint efficiency, $J = 1$ is used for seamless tube

$$\text{Therefore, } t_t = (3.6749 \times 32.46) / [(2 \times 538 \times 1) - 3.6749] \\ = 0.111 \text{ mm}$$

The specified thickness is 4.85 mm. Therefore, the selected tube is suitable for this service.

2. Calandria sheet thickness calculation

$$\text{Thickness is given by: } t_s = \frac{PD_o}{2fJ + P} \\ = (3.6749 \times 785) / [(2 \times 980 \times 0.85) + 3.6749] \\ = 1.73 \text{ mm}$$

Normally, the corrosion allowance of 3 mm is used for carbon steel.

It may be taken as $t_s = 10$ mm

3. Tube sheet thickness

Please refer **module #2 (section 2.3.5)** for the calculation of tube sheet thickness according to the TEMA code and the minimum tube sheet thickness as per IS:4503 specification also needs to be checked.

4. Evaporator drum diameter determination

The following equation helps to estimate the drum diameter. The diameter of the drum may be same as that of the calandria. However, it is necessary to check the size from the point of satisfactory entrainment separation (**[5] page 253**).

$$R_d = \left(\frac{V}{A} \right) / \left(0.0172 \times \sqrt{(\rho_l - \rho_v) / \rho_v} \right)$$

where, V = volumetric flow rate of vapor [m³/s]

A = cross sectional area of drum

For drums having wire mesh as entrainment separator device, R_d may be taken as 1.3.

$$A = \left(\frac{V}{R_d \times \left(0.0172 \times \sqrt{(\rho_l - \rho_v) / \rho_v} \right)} \right) \\ = (2.57) / [1.3 \times 0.0172 \times \sqrt{\{(1050 - 0.757) / 0.757\}}] \\ = 3.087 \text{ m}^2$$

$$\begin{aligned}\text{The drum diameter} &= \sqrt{\{4 \times 3.087\}/3.14} \\ &= 1.98 \text{ m}\end{aligned}$$

Drum height is usually taken as 2 to 5 times of tube sheet diameter

Thus, the drum height = $4 \times 0.788 = 3.152 \text{ m}$

The tube length is in between the border line of short tube (4 to 10') and long tube ($\geq 12'$). Therefore higher head space is required to arrest entrainment by mis-tallying deflector plates.

5. Drum thickness

Drum is operating at 1.3317 bar pressure

Design pressure = 1.398 bar

$$= 1.4253 \text{ kgf/cm}^2$$

$$\text{Drum thickness: } t_d = \frac{PD_o}{2fJ + P}$$

$$= (1.4253 \times 785) / [(2 \times 980 \times 0.85) + 1.4253]$$

$$= 0.671 \text{ mm}$$

Therefore the same thickness of 10 mm for both the drum and calandria sheet may be used including the tolerance for corrosion.

Note: The drum thickness is to be calculated based on the external pressure if the drum is under vacuum.

Practice problem:

A triple-effect forward feed evaporator of the long-tube vertical type is to be used to concentrate 4,000 kg/h of a 9.5% solution of caustic soda available at 40°C to 50% solution. Saturated steam at 3.5 kg.cm⁻² is available. A vacuum of 700 mm Hg is maintained in the last effect. The overall heat transfer coefficients are 5800, 3300 and 2400 Wm⁻² °C⁻¹, corrected for BPEs may be used for the 1st, 2nd and 3rd effects respectively. Calculate the heat transfer area required (assume equal areas in all three effects), steam economy and rate of steam consumption.

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